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Comparison between hydrogen fuel cell vehicles and bio-diesel vehicles

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ABSTRACT:

Performance simulation results are presented for fuel cell/battery hybrid vehicle concepts and for highly efficient combustion engine vehicles using bio-diesel fuel. The bio-diesel concept takes departure in the commercial Volkswagen Lupo TDI-3L motorcar modeled for a road-based driving-cycle of mixed urban and highway segments. This is compared to new hybrid concepts using hydrogen as fuel. Theoretically, the fuel cell cars can achieve a higher average efficiency than the common-rail diesel engine used in the Lupo. However, in practice the difference is diminished. Ongoing development of low-weight batteries such as lithium-ion batteries for automotive uses (scaled up from the current versions used in consumer electronic devices) is essential for achieving the optimum hybrid vehicle performance. Assessment of alternative vehicle concepts must include economic and environmental impacts. These have been addressed by the life-cycle analysis methodology.

Keywords*:* Hydrogen vehicles, hybrid fuel cell/battery car, common-rail diesel car, efficiency, environmental impacts

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1. Introduction

The aim of this communication is to compare fuel cell vehicles using hydrogen as a fuel with internal combustion vehicles using a biofuel such as biodiesel.

Current biomass use in the energy sector is mostly by direct combustion. This is an inappropriate use, because biomass offers exceptional possibilities for covering energy needs for transportation, which are difficult to meet with any other sustainable energy source. It is therefore reasonable to work towards a future, where biomass is converted to fuels suited for vehicle application, whether fluid or gaseous. The simplest such biofuel is biodiesel, because it can be used in existing diesel engines without any modification. This is not the case for fuels such as methanol, ethanol, dimethyl ether (DME), synthetic diesel fuels or hydrogen, all of which can also be derived from biomass.

Hydrogen derived from (often intermittently available) renewable sources such as wind or solar power is one proposed energy carrier for the future. Efficient use in the transportation sector requires the use of a fuel cell plus an electric motor. The most likely technology to reach early viability is a hybrid concept with enough traction batteries to allow the fuel cell rating to equal something like the average power needed by the vehicle, rather than the peak power. The reason for this is that the fuel cell is the component most in need of cost reduction, and quite possibly never able to reach a cost making a purely fuel cell-driven vehicle economic. The advanced batteries needed for weight reasons are also presently out of range cost-wise, but studies have shown that an optimal hybrid concept requires much less battery rating then a stand-alone electric vehicle [1-3].

These two vehicle concepts will be compared in terms of performance, energy efficiency and environmental impacts, using life-cycle analysis [4]. Direct costs will be only briefly discussed, as they are highly uncertain. The tool used for these comparisons is the modular software-package ADVISOR [4], which is well tested and offer a range of simple, parametrised sub-models or more detailed physical models for the engine, the fuel cell stack, the traction batteries, the electric motor, the exhaust control, the transmission and entire power train including controls and control strategies. The modules can easily be modified or replaced, which in this study is done to reflect the particular vehicles and fuel converters considered.

2. Bio-diesel vehicles

Bio-diesel is a common name for a range of diesel-like fuels derived from biomass. The currently most common is rapeseed oil methyl ester (RME), which is available at some 1500 filling stations in Germany and is produced at the rate of 3×10^9 kg/y worldwide [5]. In a global renewable energy scenario [1,6], future production of biofuels would be from agricultural and forestry residues rather than from grains suitable for food or fodder. This still allows biofuels with diesel-like properties to be produced, although at a slightly higher cost than for the rapeseed oil (a similar difference exists between ethanol produced from sugar or from plant residues).

The engines using bio-diesel fuel are of the generation of advanced compression ignition diesel engines (CI, the air is compressed before mixing with a controlled amount of fuel - a key reason for achieving higher efficiency than the Otto engines - and the high temperature associated with the compression allows ignition without spark creation), that have appeared on the automotive market during the last ten years. They use the high-pressure common rail injection principle, which has increased the energy efficiency of diesel vehicles by some 30% relative to comparable Otto engines using gasoline as a fuel. This is interesting because diesel fuel has traditionally been considered an inferior fuel relative to gasoline, with lower efficiency and more undesirable emissions. However, the introduction of turbocharged direct injection (TDI) and electronic control changed that in favour of diesel engine operation. The high-pressure (currently around 140 MPa) common rail principle solved the problem of pulverising diesel droplets to a small particle size and thereby reducing the amount of unburned fuel. Computerised control allows a rapid injection with the main stage surrounded by two minor injection stages serving to reduce noise and reduce unburned fuel while increasing exit flow temperature, which again reduces pollutant emissions.

The present performance simulation is based on a mixed driving cycle of total length 89 km and composed of pieces from European and North American standard cycles, as shown at the top of Figure 1. The vehicle considered is based on the Volkswagen Lupo TDI 3L, a 4-5 passenger car with high performance and exceptionally low fuel consumption (about 1 MJ/km), produced from 1999 to 2004. Its common rail diesel engine accepts bio-diesel fuel without adjustment, and its advanced "tiptronic" automatic gearbox is controlled by a choice of computer programs, with the "ecological program" giving an average fuel efficiency above 30 km per litre. Unlike some more recent common rail diesel cars, the Lupo catalyst exhaust control has modest particulate and NO_x reduction capability. Still, it meets the 2005 emission requirements of the European Union (the "Euro4 requirements"). The fuel converter module used in the simulation is based on an earlier 60 kW engine used by Volks-wagen and Mercedes, for which complete fuel and environmental performance measurements have been made [7], but adjusted to conform to the measured fuel use and emissions of the Lupo [8,9]. A series connection is used, with the fuel cell generated electricity being fed into the battery rather than directly to the motor. After assuring that the measured data for conventional diesel operation could be reproduced, the fuel characteristics were changed to those of bio-diesel (using current European norm specifications), which relative to the fossil fuel-based diesel fuel is assumed to have 25% less CO emissions, 10% higher NO_x emissions, 40% less particulate emissions and 80% less hydrocarbon carry-through [5]. The fuel efficiency of 3 litres per 100 km was assumed unchanged.

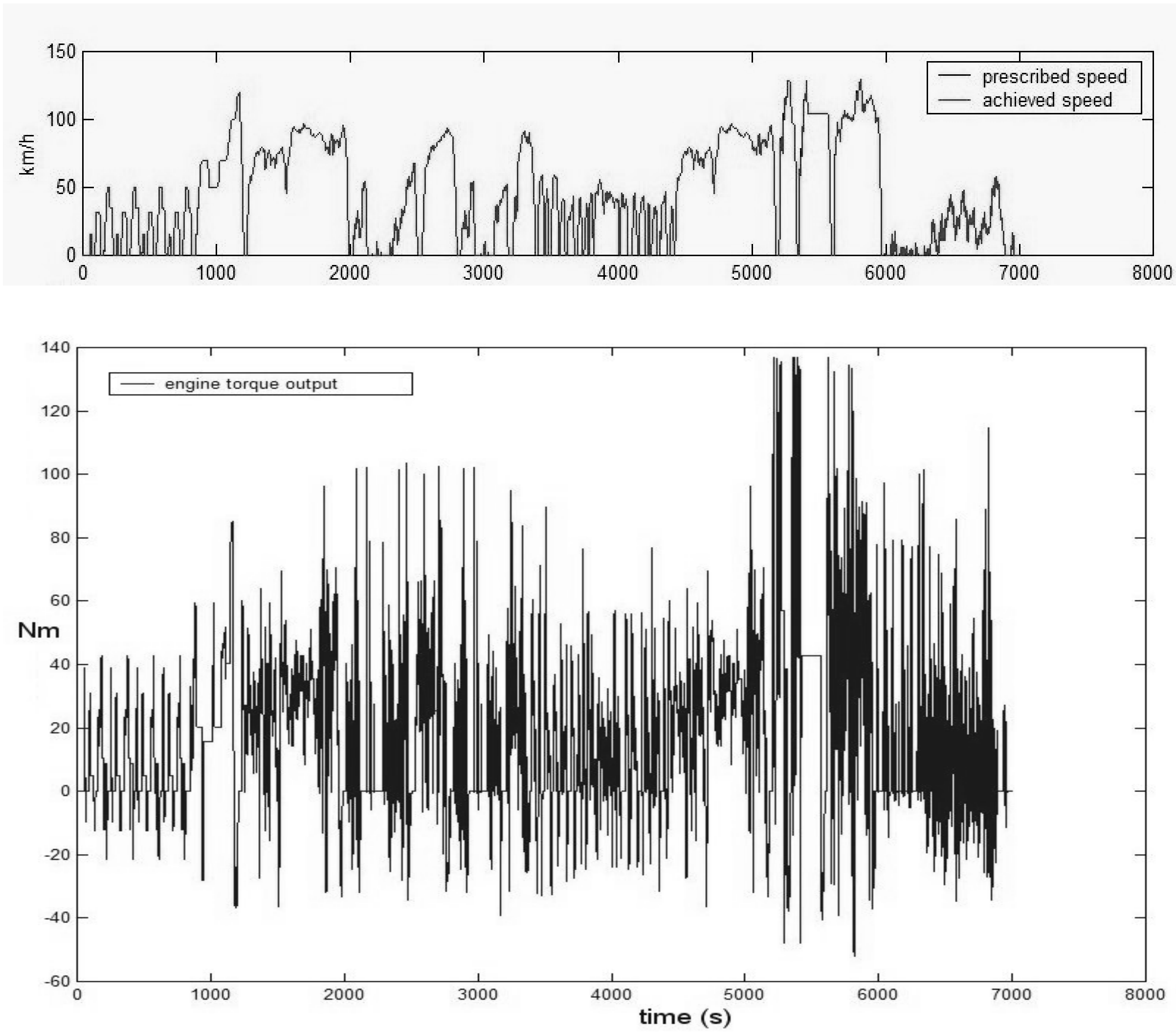


Figure 1. As function of time (in seconds), the top part shows the prescribed and achieved driving speeds (identical except for a few seconds) in km/h, and the bottom part shows the realised engine torque output in Nm, for the Lupo bio-diesel simulation.

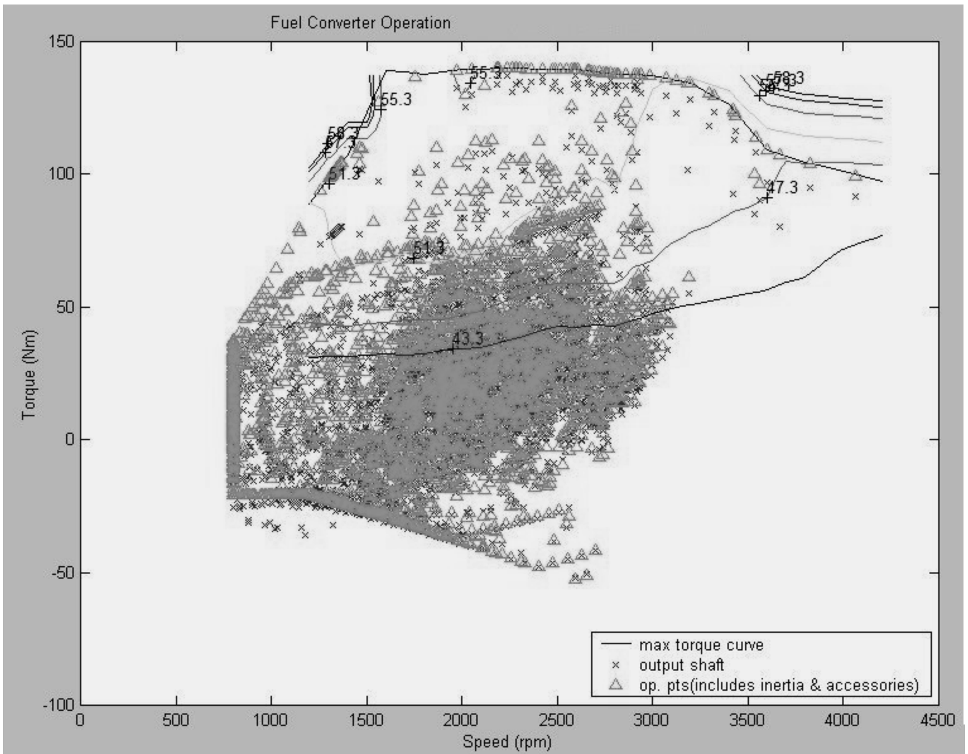


Figure 2.

Operating points of the Lupo bio-diesel engine during the prescribed driving cycle, as function of engine axis revolutions per minute and realised torque in Nm. The upper curve with operating points represents the maximum achievable torque. Shaft output values are denoted by "×".

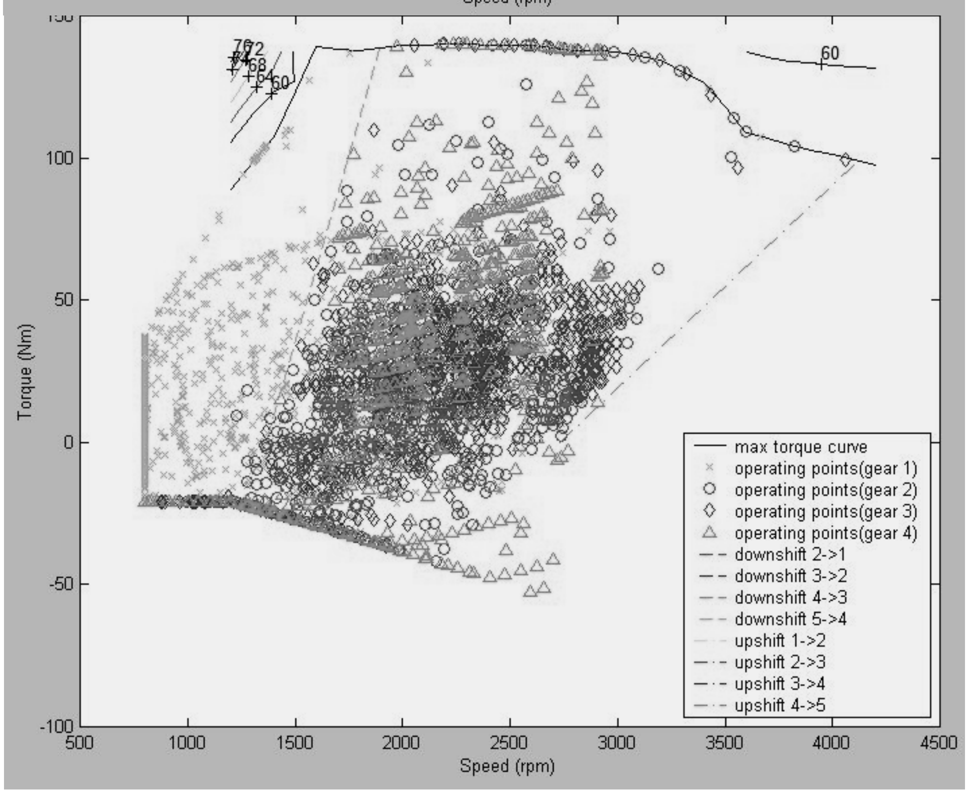


Figure 3.

Gearbox operating points from the bio-diesel car simulation, as function of engine revolutions and torque. It is seen that operation at gear exchange level 1 is occurring only for low rotational engine speeds, while operation at other gear levels (2-4) occurs at many different speed-torque relations.

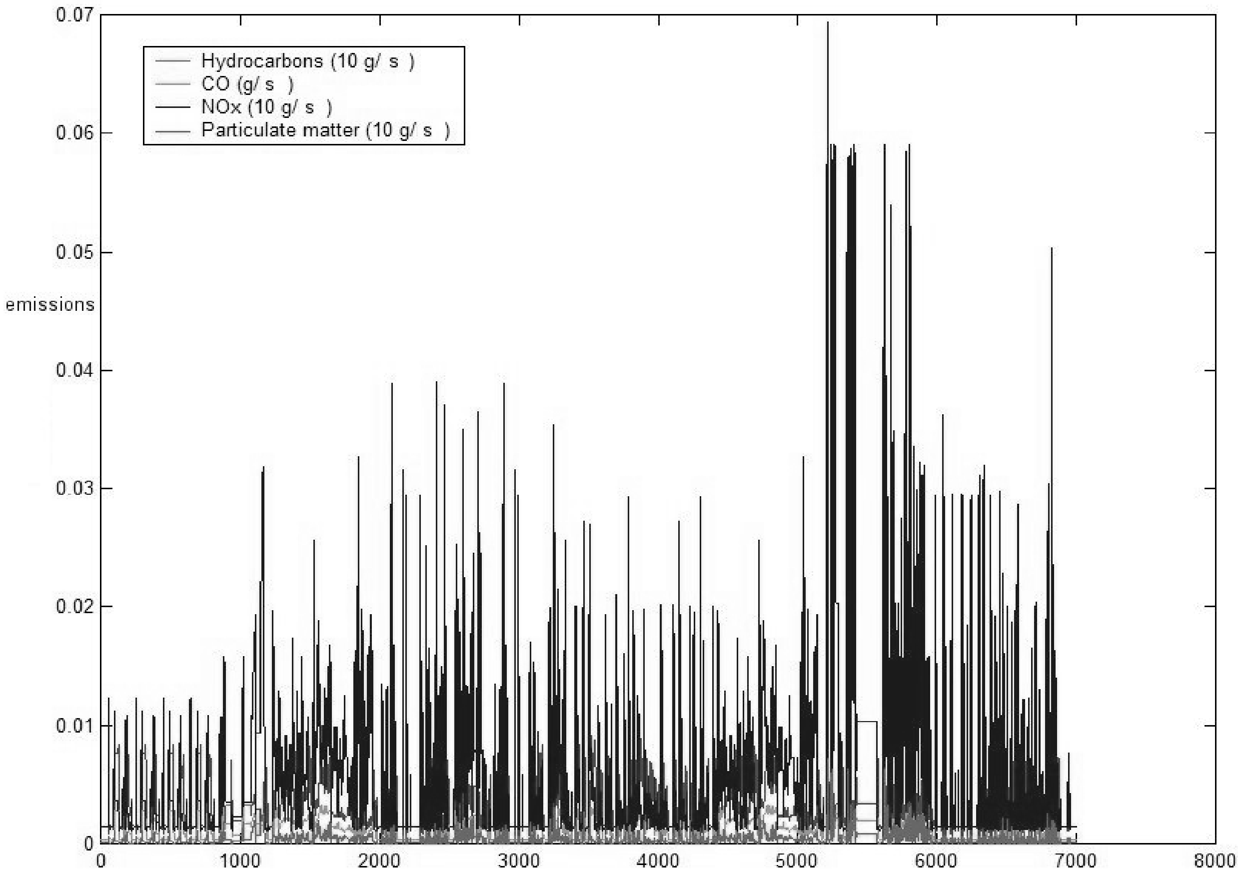


Figure 4. Emissions along the driving cycle for the bio-diesel Lupo, in 10 g/s (except CO in g/s).

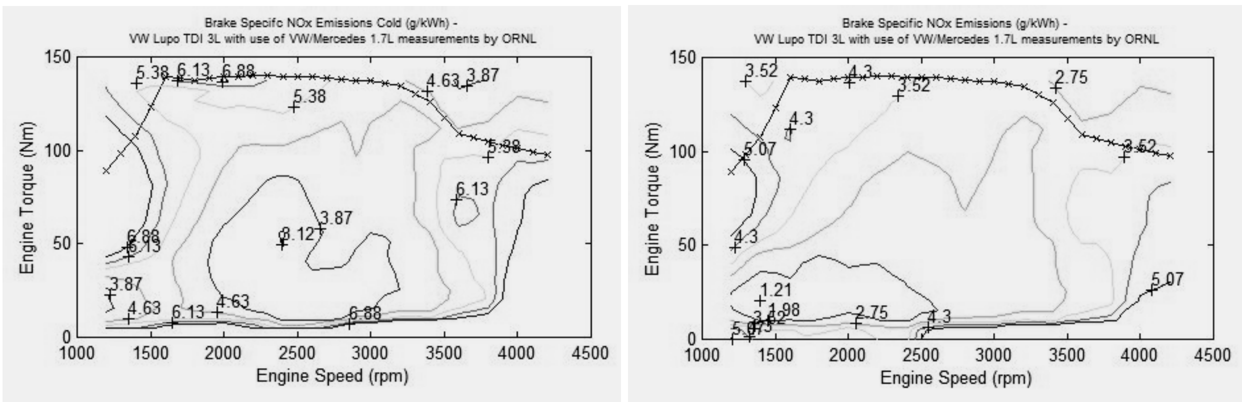


Figure 5. Efficiency of exhaust control for the bio-diesel Lupo, given as non-retained emissions in g per kWh of engine power output, as function of engine rotational speed and torque, either for a cold engine (left) or a hot engine at normal operating temperature (right).

The bottom part of Figure 1 shows the engine torque output during the driving cycle, and Figure 2 shows the operating points for the entire trip, as function of torque and engine rotational speed. The gear exchange level choice by the automatic transmission is shown in Figure 3, also for each calculated operating point along the driving cycle. The data in Figure 2 indicates that the internal combustion engine rarely operates at maximum efficiency (59%), and most of the time under 40%. The average efficiency for the entire trip is 37%. The 3 litres of bio-diesel per 100 km is equivalent to 2.4 litres of gasoline per 100 km.

Figure 4 shows the emissions during the trip, as a function of driving time. The most significant emissions are of nitrous oxides. As illustrated in Figure 5, cold-start behaviour was modelled. For the NO_x emissions, more than a doubling is found for low engine speeds and low torques, but still the overall emissions in the early part of Figure 4 are not nearly as large as those during high-speed driving on the highway part of the driving cycle. Average emissions for the entire trip is found to be 0.029 g/km unburned hydrocarbons, 0.075 g/km CO and 0.278 g/km NO_x, plus negligible particulates. The corresponding figures for the ordinary diesel Lupo are 0.03, 0.10, 0.25 g/km and 0.02 g/km particulates [1,8]. The modelled efficiency of the Lupo catalyst exhaust control varies between 5% and 100% for NO_x suppression, is generally around 95% for CO and around 50% for particulates.

3. Hybrid fuel cell/battery vehicle

For the hybrid car, surplus power from the fuel cell is used to recharge the batteries, which at the end of the driving cycle are required to be left as well charged as at the cycle start. The hybrid solution needs a fuel cell rated at 20 kW with an average efficiency of 57%, plus a 5 kWh Li-ion battery. Both batteries and fuel cells are emerging technologies, as regards efficiency and durability goals. The battery weight is 113 kg and would be about 2.5 times more for NiMeH or lead-acid batteries, starting to have a negative effect on performance due to increased overall car weight, in an obviously vicious circle. For comparison, a pure battery solution for the vehicle in question could not reach the required 650 km range, and a pure fuel cell vehicle would need a higher rating of 30-40 kW [2]. As for the bio-diesel car, the maximum payload of the hybrid car is 340 kg, and the average load assumed in the simulations is 136 kg of passengers and freight. Power level time series are shown in Figure 6.

In contrast to the diesel vehicle, the fuel cell version is spending most of the operating time in a state of high fuel conversion efficiency. The average efficiency is as high as 57% for the fuel cell modelled, with a maximum efficiency of 59% [1]. The behaviour as function of going through the driving cycle is shown in Figure 9, and for comparison the efficiency of the bio-diesel car in Figure 8. Here the losses are larger and associated with engine operation, while for the hybrid car, the losses are chiefly in the motor/controller operation.

The excursions in battery charge state (Figure 7) are under $\pm$ 3%, for the driving cycle considered. The hybrid solution has a better performance (higher maximum torque and better acceleration characteristics) than the corresponding pure fuel cell vehicle [6]. The batteries assumed installed are lithium-ion batteries, which have proven very successful in small-scale applications and are currently in the process of being scaled up for automotive applications at less prohibitive costs than those obtained by scaling up from the consumer product market. If conventional lead-acid batteries were used instead, the vehicle mass would be considerably higher and the performance somewhat reduced.

Figure 10 shows the distribution of losses averaged over the entire driving cycle, for the bio-diesel and the hybrid car. The latter has about half as many propulsion system losses, while other losses are similar. The hybrid car fuel use is 38.4 litres of hydrogen per 100 km, which in energy content is equivalent to 2.6 litres of gasoline per 100 km. No pollution is created by the hydrogen combustion.

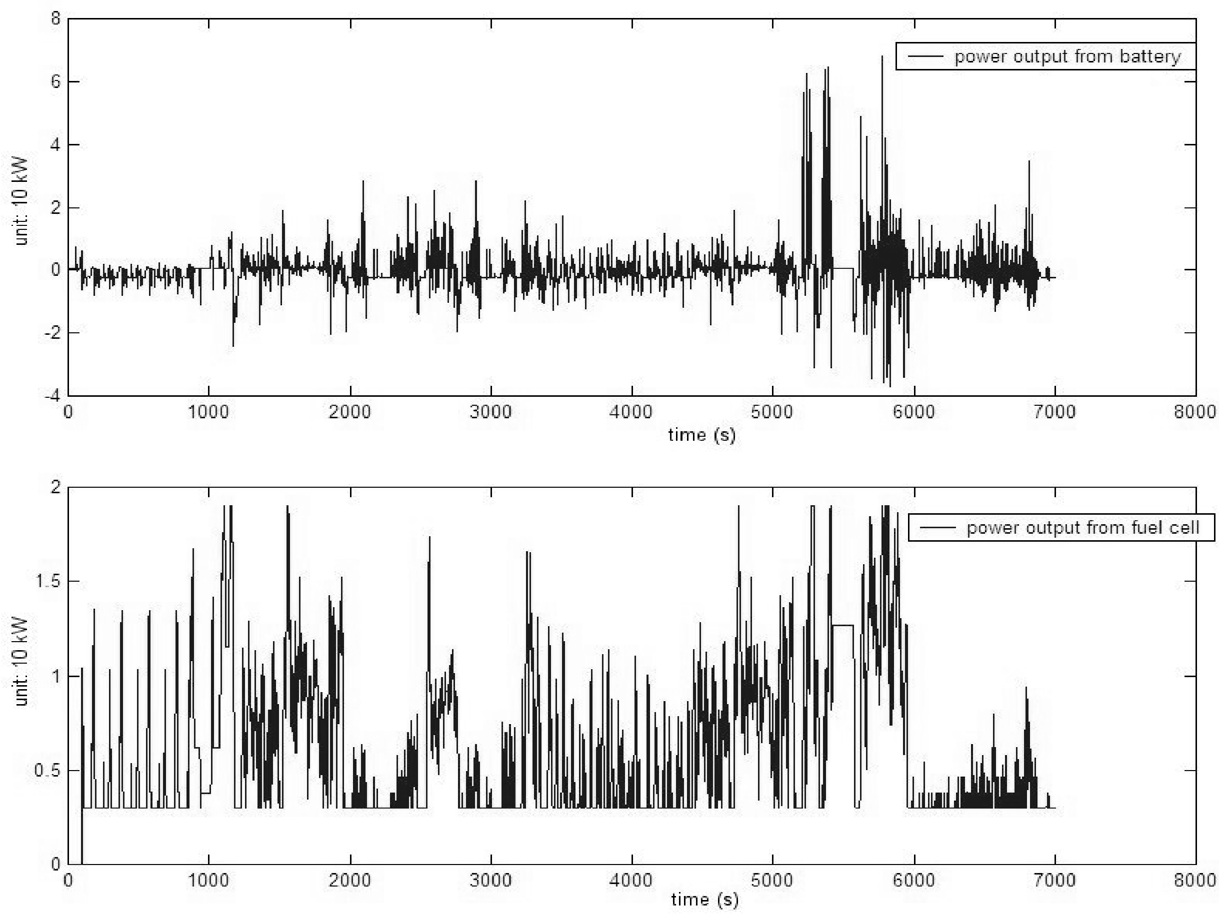


Figure 6. Power output from battery and from fuel cell to battery, for the hybrid car, in 10^4 W.

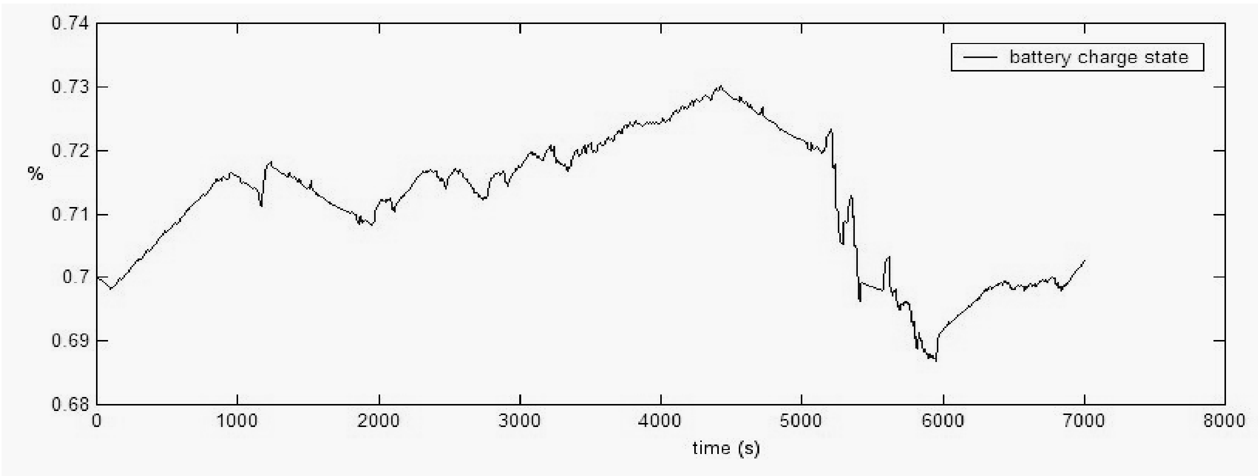


Figure 7. Battery percentage of full charge state, as function of driving distance.

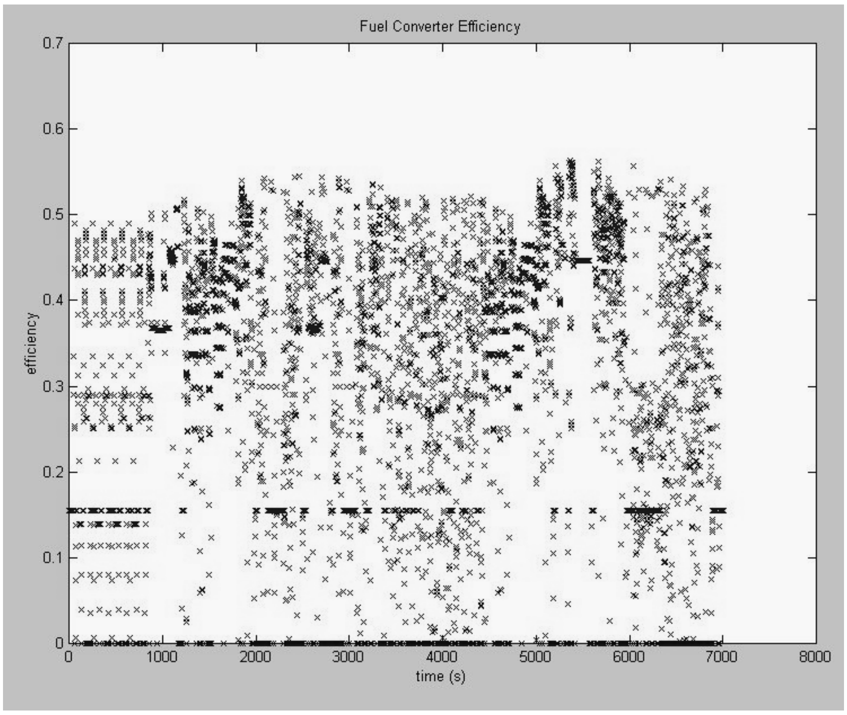


Figure 8.

Engine efficiency of the bio-diesel car, as function of driving time.

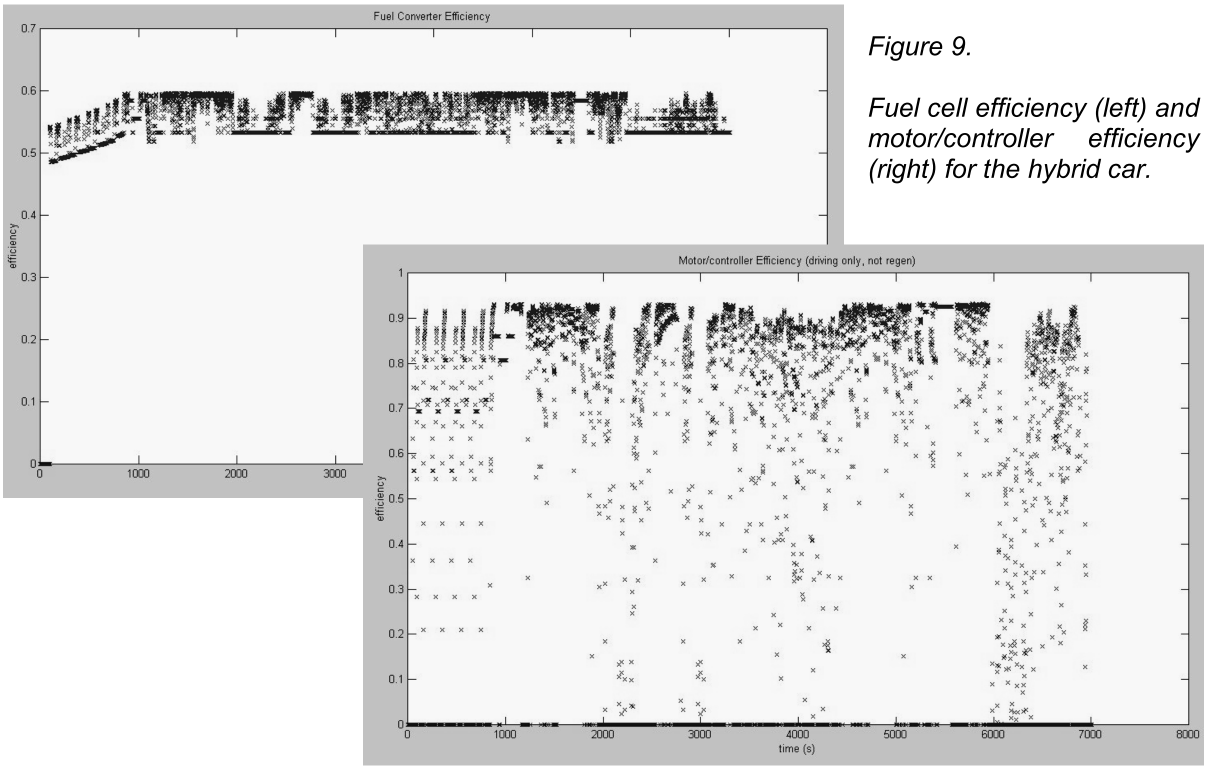


Figure 9.

Fuel cell efficiency (left) and motor/controller efficiency (right) for the hybrid car.

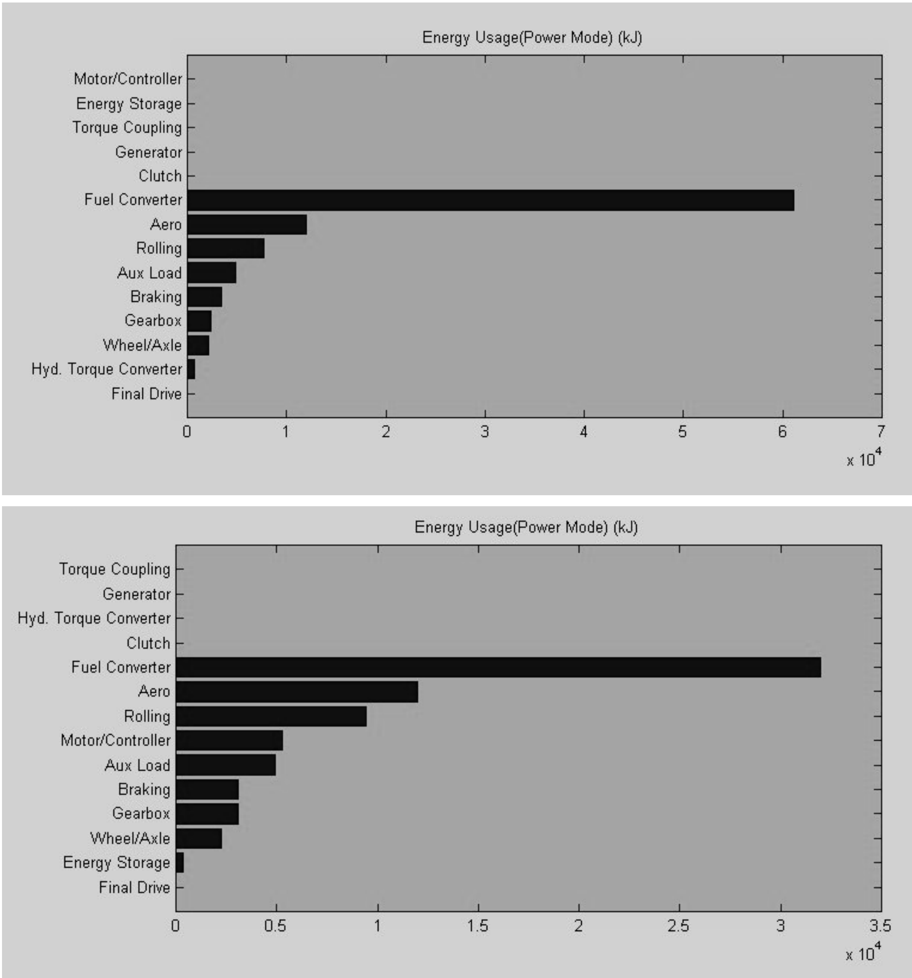


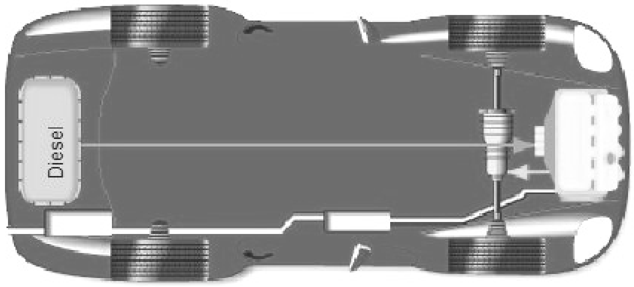
Figure 10.

Distribution of energy losses. The top figure is for the bio-diesel car, the lower one for the hybrid fuel cell/battery car. Note the different scale: the aerodynamic losses are identical for the two cars, and the rolling resistance losses nearly identical, differing only because of the higher mass (1200 kg) of the hybrid car, due to fuel cell stacks, pressure containers, motor and batteries weighing about 220 kg more than the diesel engine.

4. Conclusions

The two road vehicle types modelled are depicted in Figures 11 and 12, giving model structure and overall layout. The key feature of the car concept underlying these models is that it has high efficiency in the conventional sense, whether or not an internal combustion or a fuel cell/electric fuel converter is employed. The simulation results indicate, that the mileage advantage of the advanced hybrid car is fairly modest (13% lower fuel use for the same distance), despite a substantially higher efficiency characterising the fuel cell itself (54% higher than for the state-of-the-art diesel engine). The reason is of course, that there are more components along the power conversion pathway. However, there is an environmental advantage to the hybrid car: the absence of emissions in the operational phase [6].

The current cost of a prototype hybrid car of the kind modelled is several times the actual cost of the bio-diesel car. Development efforts should not only bring the cost of fuel cells and advanced batteries down by an order of magnitude, but should also ensure a lifetime similar to the 15-25 years valid for the bio-diesel car. The current fuel cell target lifetime and actual lifetime of Li-ion batteries, both being 5 years, will imply 2-4 replacements of the fuel cell stack during the operating period and thus the same factor of required additional cost reduction.



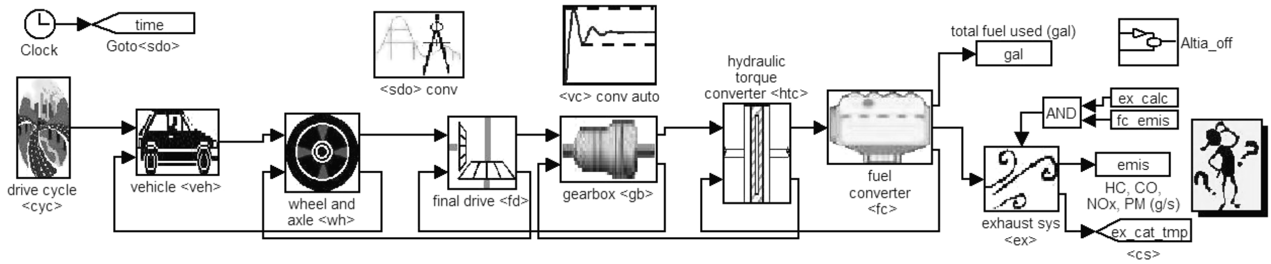
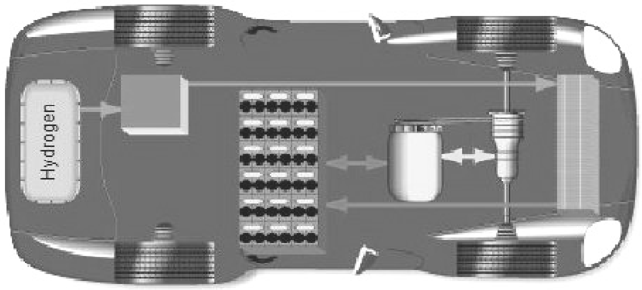


Figure 11. Model structure used for simulation of bio-diesel vehicle performance. Below are model components, and to the left a connection overview.



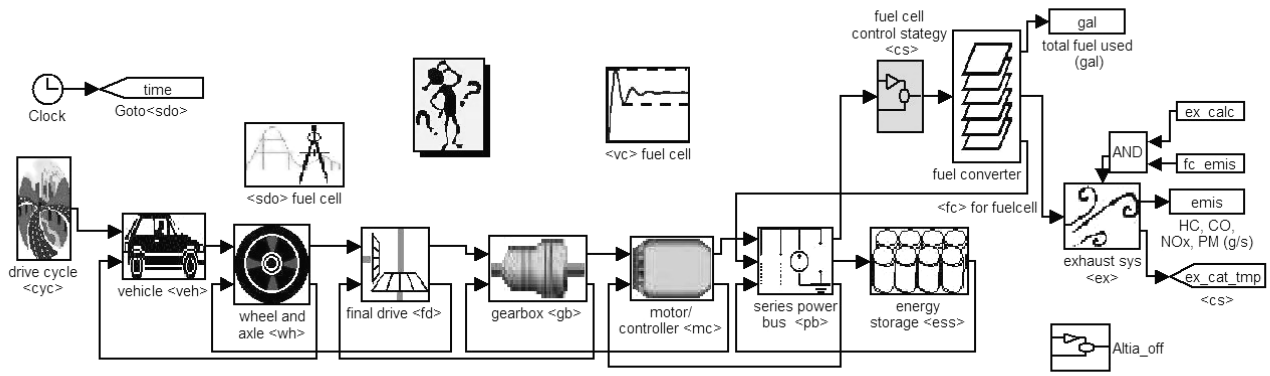


Figure 12. Model structure used for simulation of fuel cell/battery hybrid vehicle performance. Below are model components, and to the left a connection overview. The box to the right represents the controller.

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